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Blind Results for The Aerodynamic Wind Turbine Design Optimization Case Study for the IEA Task 37 on Wind Energy Systems Engineering

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Blind Results for The Aerodynamic Wind Turbine Design Optimization Case Study for the IEA Task 37 on Wind Energy Systems Engineering

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Outline

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- Problem Description
- Survey of Tools
- Comparison of Preliminary Results
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    - Optimal design
    - Performance of the optimal design
- Closing Statements

Acknowledgments

Acknowledgments

This work is a collaboration between many researchers and institutions.
The following have contributed results for this presentation:

- Michael K. McWilliam, Frederik Zahle, DTU Wind Energy
- Pietro Bortolotti, Carlo Bottasso, Technische Universitat Munchen
- Birger Luhmann, Niklas Jores, University of Stuttgart
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- Evan Gaertner, Matthew Lackner, University of Massachusetts, Amherst
- Terence Macquart, University of Bristol
- Karl Merz, SINTEF, Trondheim, Norway

The following researchers are also involved in this collaboration:

- Ozlem Ceyha, ECN
- Beatriz Mendez Lopez, CENER
- Rad Haghi, Curran Crawford, University of Victoria

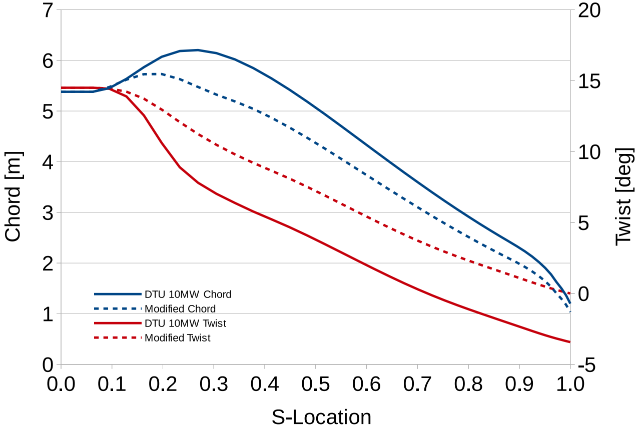
Problem Description

Research Objectives

- This IEA Task is meant to coordinate international research activities, towards the analysis of wind power plants as holistic systems
- Multi-disciplinary Design Analysis and Optimization (MDAO) is a valuable tool in systems engineering with all disciplines
- Starting with single discipline case studies because full turbine MDAO is complicated
- This will help us in the following ways:
  - Provides a baseline to help understand the differences in future studies
  - Allow more researchers to be involved by starting with simpler cases
  - Gives us experience in creating, managing and analyzing optimization case studies
- This is **less about validation and more about developing design techniques**

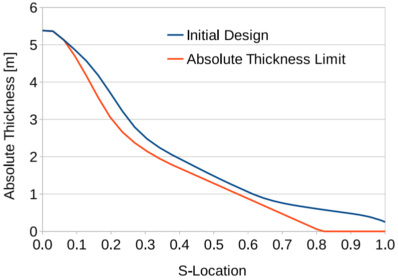
Initial Design

- Based on the DTU 10MW reference wind turbine with the following modification:
  - Reduced chord, less aggressive twist, thicker blades
  - No coning or tilt



Optimization Problem

- Load constraints based on initial design loads
- Structural considerations:
  - Minimum absolute thickness
  - Smaller center of thrust



Maximize	Annual Energy Production
Varying	
	Chord
	Twist
	Relative Thickness
subject to	
	$T \leq 1.14 \max T_0,$
	$M \leq 1.11 \max M_0,$
	Absolute thickness $\geq$ limit

Aerodynamic Analysis

- Design evaluated with steady, uniform wind without turbulence
- Turbine operates between 4 and $25m/s$
- AEP based on Weibull distribution with scale and shape 8 and 2 respectively
- Must find optimal regulation based on:
    - Design Tip-Speed-Ratio: 7.8
    - Minimum RPM: 6
    - Maximum RPM: 9.6
    - Find optimal pitch to feather when in constant speed operation

Survey of Tools

Survey of Tools

- Typical set-up:
  - Steady-state BEM with angular moment and tip-loss functions
  - Spline parameterization with approximately 15 design variables
  - Sequential Quadratic Programming (SQP)
  - Finite-difference gradients
- Some exceptions:
  - Brigham Young University/NREL:
    - Analytic adjoint gradients mixed with automatic differentiation (Tapenade)
  - University of Massachusetts, Amherst
    - The NSGA genetic optimization algorithm
  - DTU Wind Energy
    - IPOPT optimization algorithm
  - University of Stuttgart
    - Sequential Least Squares Programming
  - SINTEF
    - Complex Step Gradients

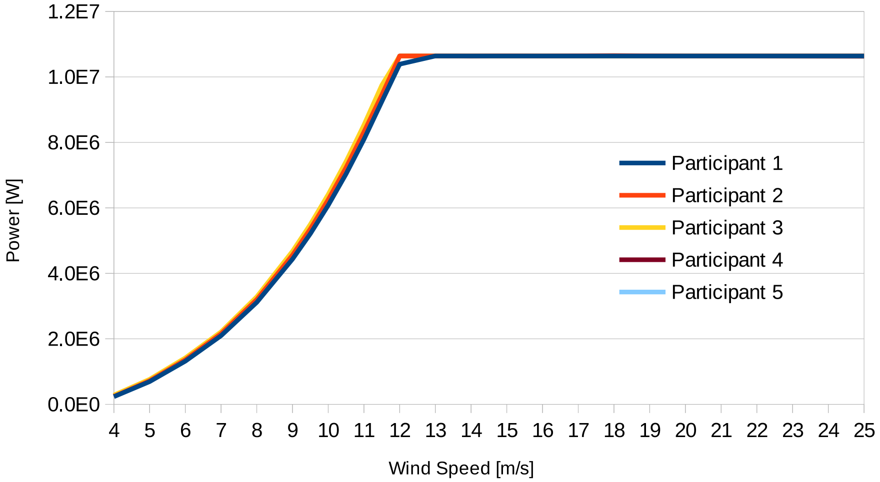
Comparison of Blind Results

The Final Blind Results

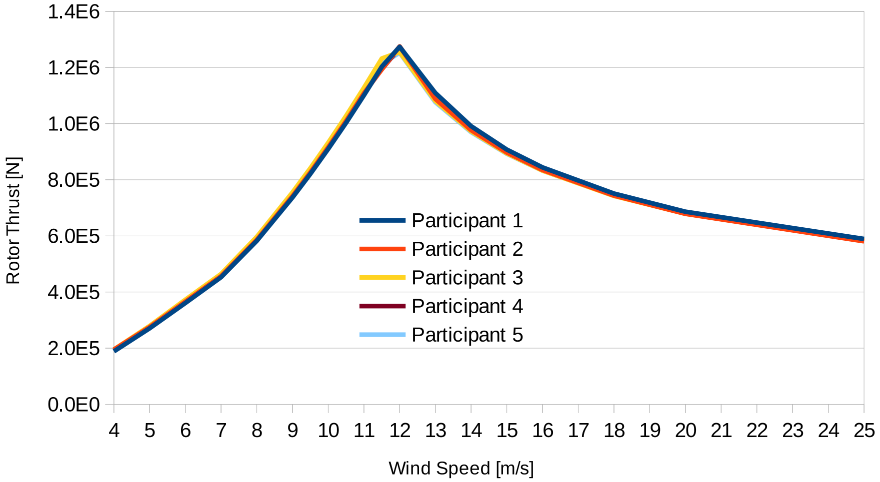
- Researchers performed optimization without seeing other results
  - The results you get without best-practices
  - Most researchers required 2 attempts because of misunderstandings
  - Some researchers did see some of the preliminary results in June (not perfectly blind)
- The source of the results is anonymous
- Next round of optimization the results will be shared openly to understand the differences

Performance of the initial design

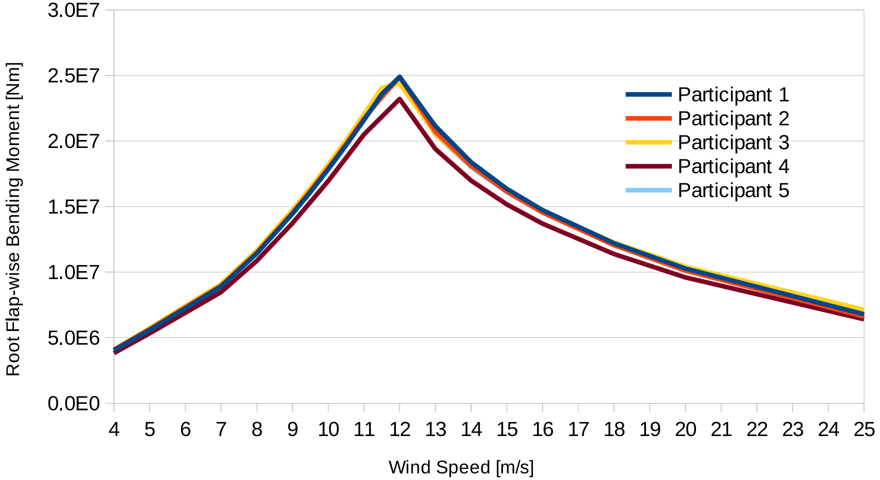
Initial Power



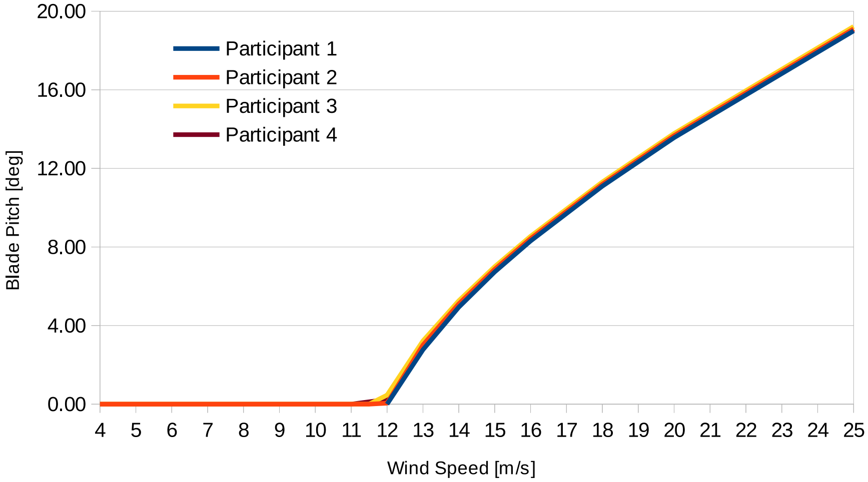
Initial Thrust



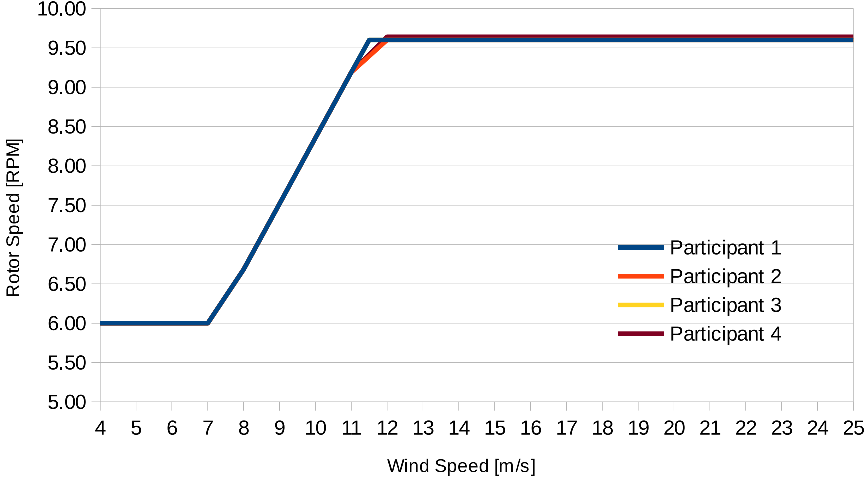
Initial Blade Root Flap-wise Bending Moment



Initial Blade Pitch



Initial Blade Rotational Rate

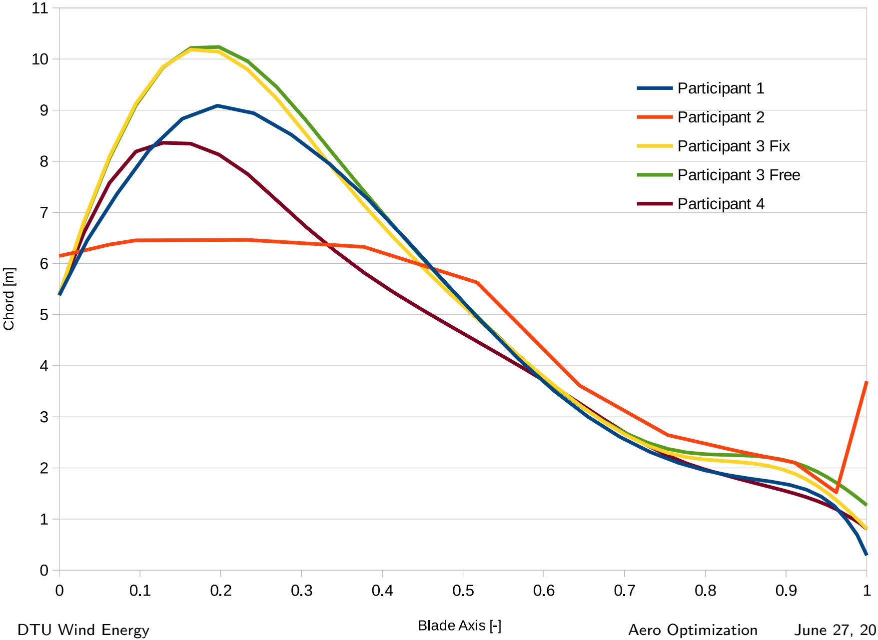


Optimal design

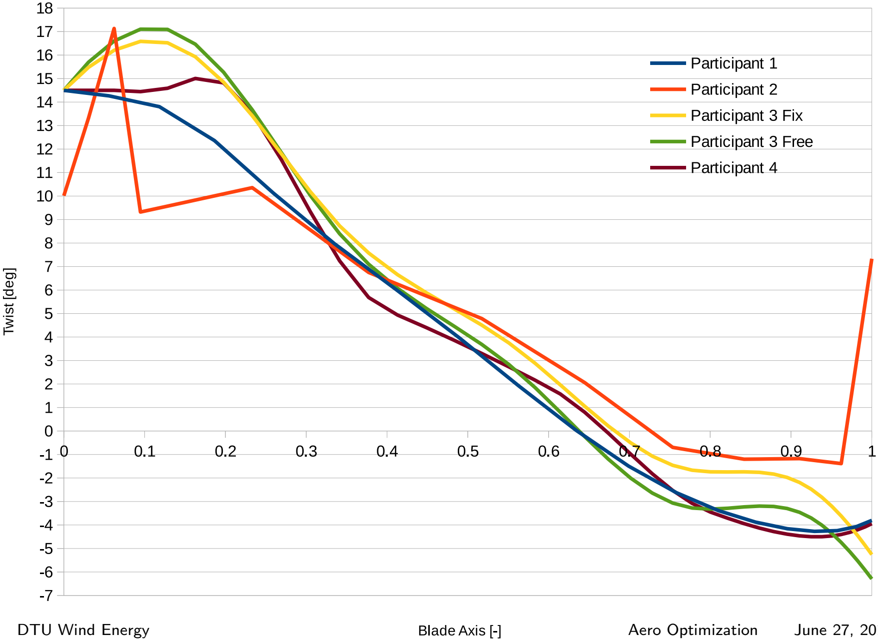
Notes on the optimization results

- Most researchers prescribed 0 pitch between 6-rated wind speed
- There is pitch setting optimization before 6 m/s
- Pitch control used to track power above rated
- Participant 3 contributed 2 results
  - The Fixed-Pitch results prescribed 0 pitch between 6-rated wind speed
  - The Free-Pitch results allowed pitch variations at near rated conditions for peak shaving

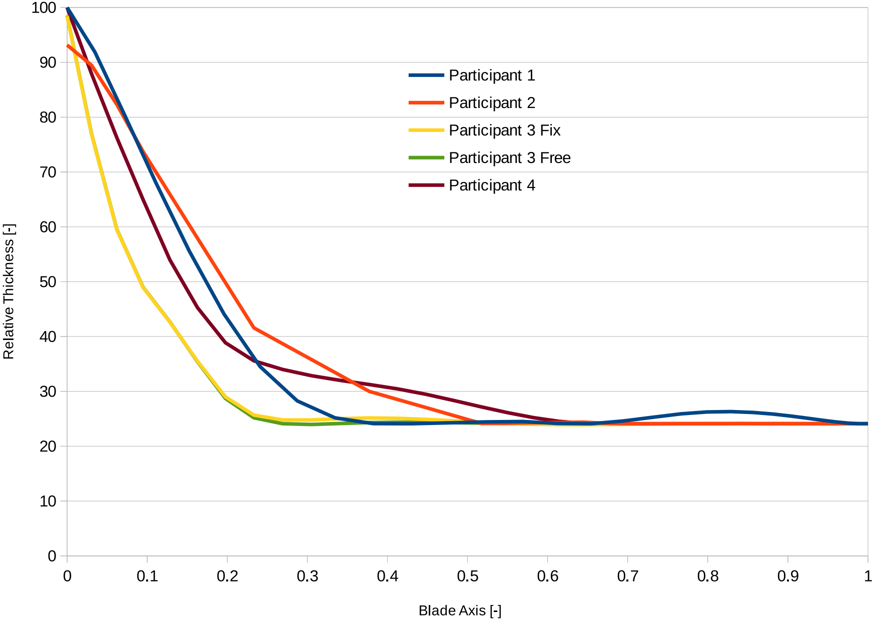
Optimal Chord



Optimal Twist



Optimal Relative Thickness



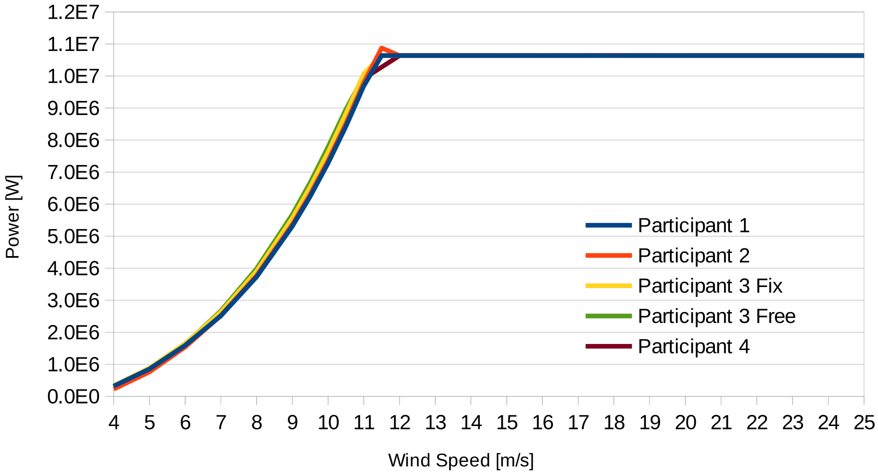
Performance of the optimal design

Improvement in AEP

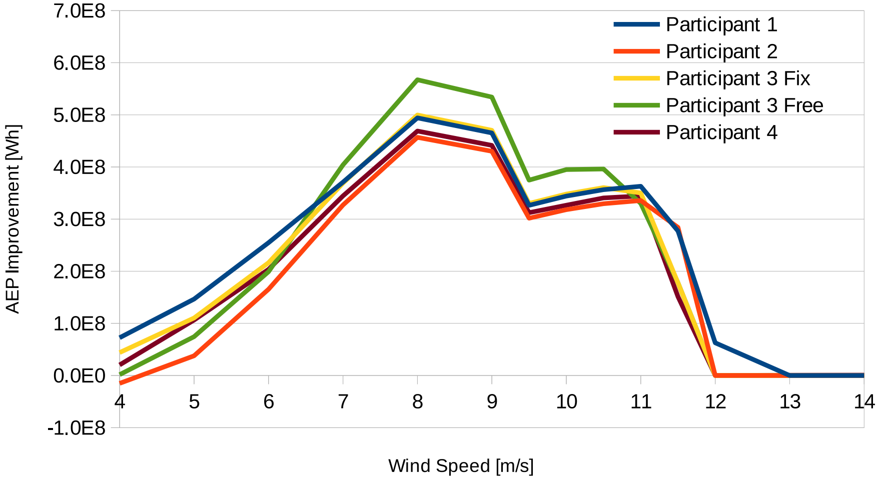
Participant	Initial AEP	Optimal AEP	Increase	T-Const	M-Const
1	28.4 GWh	31.9 GWh	12.44%	13.98%	10.98%
2	29.0 GWh	31.1 GWh	10.26%	14.27%	13.25%
3 Fix	29.5 GWh	32.8 GWh	11.11%	12.65%	11.00%
3 Free	29.5 GWh	33.0 GWh	11.71%	9.95%	11.00%
4	29.2 GWh	32.3 GWh	10.49%	13.11%	10.95%

- Participant 1 demonstrated the greatest improvement
- Good convergence in power and relative improvement
- Only 1 participant had a feasible design with an active thrust constraint
- Participant 2 had an infeasible design

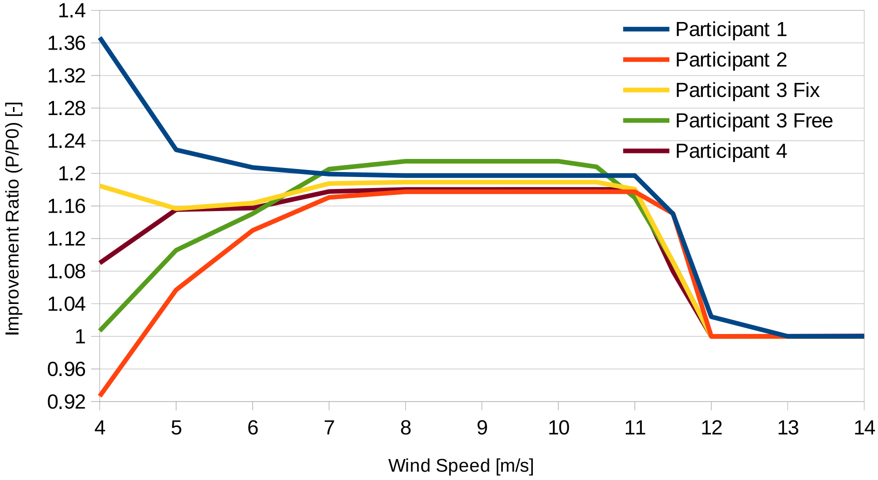
Optimal Power



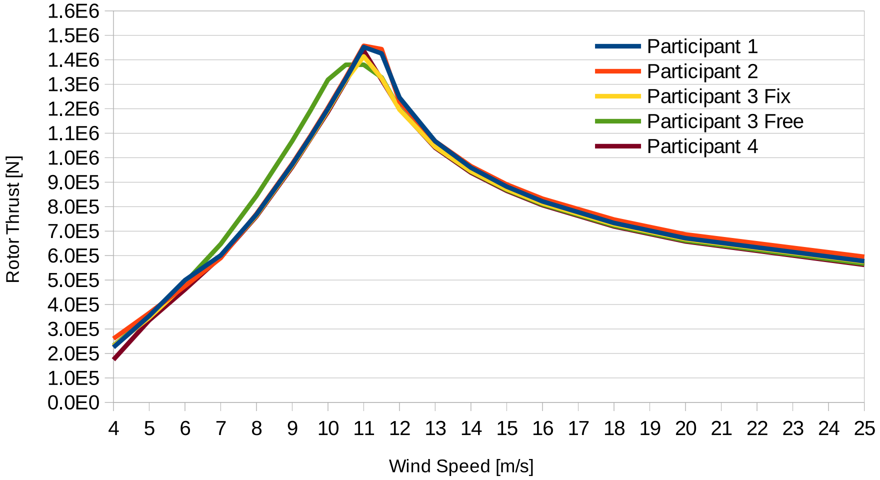
Optimal AEP Gain



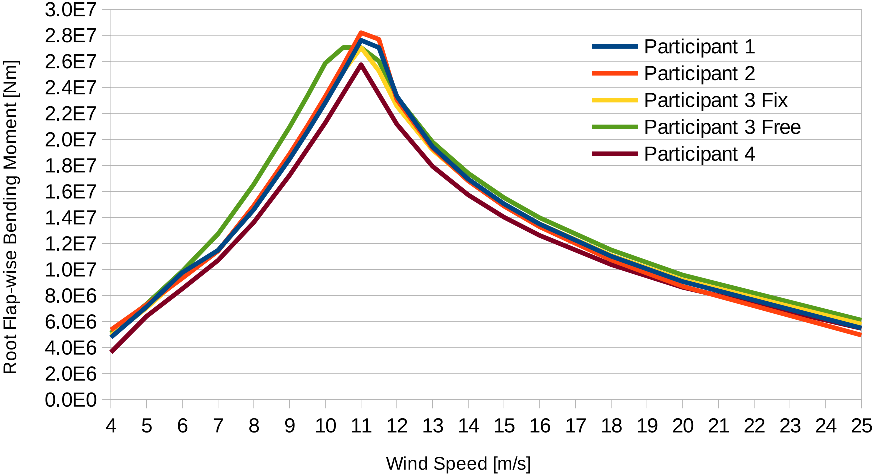
Optimal Power Ratio



Optimal Thrust

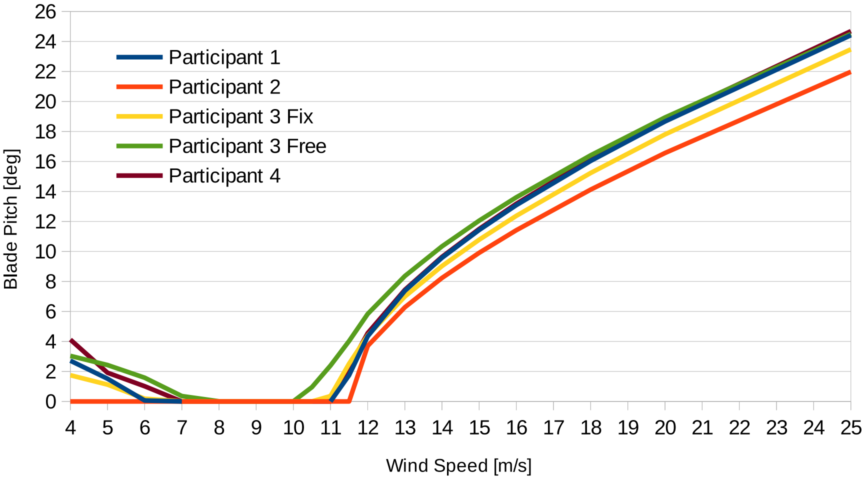


Optimal Blade Root Flap-wise Bending Moment



Optimal Pitch

- Participant 2 does not optimization pitch at lower speeds



Closing Statements

Conclusions

- IEA Task 37 is meant to explore MDAO of wind turbines
- Simple aerodynamic case study is developed
    - Based on a modified DTU 10MW Reference Turbine
    - Maximize AEP by varying chord, twist and thickness
    - Subject to thrust, moment and some geometric constraints
    - Some artificial structural considerations
    - Must solve optimal regulation strategy
    - Analysis based on steady uniform wind
- Many researchers are applying their tools to this problem
    - Most set-ups based on splines for the design variables, BEM aerodynamics with SQP optimization and finite difference gradients
    - There are differences in the optimization algorithms and gradient algorithms
- First round of blind results obtained
    - Most participants have contributed results
    - Similar performance for the initial design
    - Large variation in the optimal design and performance
    - Some indication tool differences are driving the design

Thank-you for your interest

Comments or Questions?

Please approach me after if you want to participate